INTERNATIONAL GAS TURBINE INSTITUTE
The AMERICAN SOCIETY of MECHANICAL ENGINEERS
Atlanta, Georgia USA

MARINE COMMITTEE
1996 Best Paper Award

"A Fully Enhanced Gas Turbine For Surface Ships" ASME Paper 96-GT-527

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Presented At The Interenational Gas Turbine And Aeroengine Congress & Exhibition
Birmingham, U.K. June 10-12, 1996

A.S.M.E. PAPER SUBMITTED FOR TURBO'96, MARINE SESSION

"A FULLY ENHANCED GAS TURBINE FOR SURFACE SHIPS"

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ABSTRACT:

Clearly, the advanced gas turbine has center stage in the world for converting fuel to work. The power and efficiency delivered by the advanced gas turbine have made it the predominant prime mover in the air, and increasingly so on land and sea. This paper explores the full potential offered for marine applications by the advanced gas turbine, a potential that is fully enhanced by use of available engineering options that are external to the gas generator. The enhancement options are:1) intercooling 2) thermal recuperation 3) steam injection 4) reheat 5) closed loop cooling 6) catalytic partial oxidation 7) water recovery. Of the options studied reheat involves a unique approach. Reheat is postulated to be accomplished with a new simplified technique. An autoignitable hydrogen-rich fuel is injected into the air path through the cooling passages and from the trailing edge of blades and vanes of the low pressure turbine, reheating the air prior to entry into the free power turbine.

CHRONICLE OF MARINE LOCOMOTION

Seafaring people have long searched for the "optimum means" of getting from point A to point B on the surface of the ocean. In the beginning, oars were the only means and for centuries oceans were so traversed. With evolution, the several hundred man galleys of Roman and Chinese ships became a wonder of marine engineering. Sail was introduced by a farsighted development program, no doubt, and sail had to have been preceded by the development of suitable cloth. Despite the many disadvantages of wind power and sail, it gradually made a place for itself in the world's navies and eventually, with the development of canvas, became the "optimum means" of ocean exploration and transport for the next millennia. Oars retained a niche in the "optimum means" market. Two centuries ago, James Watt invented the coal burning boiler/reciprocating steam engine cycle for land applications. One century later, despite their many limitations, necessary adaptations, and burdensome fuel requirement, the steam engine, and later in the century, De Laval's steam turbine became a superior means for ship propulsion. Sail declined. Also in the last century, Rudolph Diesel introduced a new oil fired reciprocating engine. While Mr. Diesel said it could never be used in mobile applications, developments proved otherwise and this engine remains in widespread use at sea. The gas turbine, a non-reciprocating engine, was invented early in this century by Hans Holzwarth, and it has subsequently reached great heights in aircraft service. Adaptations of these advanced aircraft engines are in operation on land and at sea. History suggests the search for improvement goes on unabated. It is ineluctable that the highly successful gas turbine, *adapted and improved from the present air/ground application*, is predestined to provide the seafaring with their newest "optimum means."

The Advanced Aircraft Engine As a Prime Mover

In the last half century remarkable gains in aircraft engine performance have been achieved. These gains have been accomplished despite design weight restraints and the inordinate demand on reliability imposed by flight requirements. The gain in power and efficiency is the result of the inexorable increase in pressure, temperature, and gas flow at turbine entry, together with reduction in aerodynamic losses compressing inlet air. Today's elevated firing temperature is achieved by complex turbine blade cooling strategies and the use of super alloys with special castings and coatings, allowing gas temperatures near the melting point of the metal! Despite the rigorous duty cycle and total dependance on state-of-the-art high technology, many millions of operating hours, all on liquid fuels, have firmly established the long-term durability, reliability, availability, and maintainability of the advanced aircraft engine. The engine can be considered suitable for any alternative duty imaginable. The advanced aircraft engine, suitably modified, can and is now supplying the shaft power required for propulsion of surface ships. This paper addresses the question: How can future marine gas turbines fully benefit from performance enhancements *being developed* for stationary applications? The enhanced gas turbine scheduled for surface ships is intercooled and regenerated (ICR) and constructed of aircraft engine modules: The Westinghouse-Rolls-Royce (WR21) ICR. An alternative aeroderivative gas turbine with a regenerator is the General Electric LM2500R. A third aeroderivative gas turbine cycle, a *fully* enhanced cycle, is the subject of this paper. (See figure 1. for the cycle comparison)

THE MARINE AERODERIVATIVE GAS TURBINE

The multi-shaft design of the advanced aircraft engine readily lends itself to additional engineering techniques and processes routinely employed outside the aircraft industry. When integrated into the cycle, these techniques significantly increase the shaft power delivered and thermal efficiency achieved in the overall cycle employing what is basically the advanced aircraft engine derivative.

Marine applications for gas turbines have a set of unique requirements not associated with the nominal ground installation. A key question is: In meeting the special needs of marine gas turbines, how many of the known and proven gas turbine performance enhancements can profitably be incorporated in the gas turbine powered surface ship?

Comparing Shaft Power Requirements for Land and Sea

An essential requirement common to the independent ground based utility and the shipboard propulsion plant is that both must continue to meet the demand for shaft power after losing the single largest source of power. The problem is one of spinning reserve. The ship board units are limited in number and necessary backup capacity and inordinate level of part load operation. The land based utility, however, has the whole array of gas turbine options to meet the demand, from the least expensive/least efficient that rarely run to the most expensive/most efficient units that run continuously meeting the base load. The shipboard engine must represent the judicious choice for only one type and size gas turbine of fixed power and thermal efficiency to meet the whole range of power requirements from full speed to riding at anchor. The consequence of having restricted gas turbine options is that average annual thermal efficiency is set by the achievable average part load efficiency. The fully enhanced gas turbine must exhibit the flexibility to be the optimum at delivering both shaft power and shaft work while operating at the average power.

As with the aircraft engine, the volume and weight that can be devoted to the ship's propulsion plant are restricted. The performance gains resulting from the proposed gas turbine enhancements must come at little or no increase in these two parameters. Additionally, the maintainability and survivability of the enhanced gas turbine plant on the high sea in a self-contained ship is a unique consideration relative to a readily supportable and accessible ground based gas turbine power plant. Gas turbine performance gains from proposed enhancements must not come at the expense of these unique operational obligations. Additionally, marine gas turbine power plants that require high purity makeup water are at a major disadvantage unless water sources can be identified that do not overburden the constrained and limited space/resources of the isolated ship.

Options Available for Enhancing Gas Turbine Performance

This paper will discuss standard engineering options for enhancing the performance of ground-based aeroderivative gas turbines, applicability for surface ship propulsion, and several unique means for implementing the enhancements. These performance enhancement options are:

1. **Intercooling**
2. **Thermal recuperation**
3. **Steam Injection**
4. **Reheat**
5. **Closed circuit cooling**
6. **Chemical recuperation**
7. **Recovery of cycle water**

The enhancement options apropos to surface ships will be incorporated into a conceptual gas turbine powered cycle that is intended to maximize power and efficiency and will be deemed "fully enhanced."

1. **INTERCOOLING**

Intercooling is the most common of enhancement techniques for reducing work in compressing gas. If the resulting compressor discharge temperature is significantly less than the exhaust temperature, a certain amount of heat in the gas turbine exhaust becomes available for recovery in a recuperator. The heat removed by the intercooler from the partially compressed air is, however, usually at too low a temperature to be returned to the cycle and must be rejected. Intercooling is a readily available technique for enhancing performance of a high compression ratio gas turbine for surface propulsion and is used successfully in the WR21.(See Figure 1.)

2. **THERMAL RECUPERATION**

Both the WR21 ICR and the LM2500R employ a recuperator (exhaust gas-to-compressed air heat exchanger) to recover high grade heat in the gas turbine exhaust by means of a counter-current flow of compressor discharge air that, after heating, flows on to the combustor. The WR21 at full load is able to reduce the stack temperature to _ 672ºF, and down to 521ºF at part load. Without the intercooler, the high pressure air temperature would not allow a significant reduction in the full load gas turbine exhaust temperature. The LM2500R is only effective at part load in lowering the stack temperature. Far greater benefit from the recuperator can be obtained, however, if the compressed air exiting the high pressure compressor can be cooled before it enters the recuperator.

A High Pressure Heat Exchanger (HPQX), a New Enhancement Option

A new heat exchanger is introduced between the compressor discharge and the recuperator. The high pressure shell and tube heat exchanger cools the high pressure compressor discharge air. This is accomplished with the flow of hot air across finned tubes. The tubes contain a two-phase fluid of distillate and water, initially at ambient conditions, flowing counter-current to the air flow. The compressed air and tube coils are contained within a pressure vessel shell. The in-tube flow of water/distillate is vaporized and superheated and the gas mixture exits the exchanger at a close temperature approach to the compressor discharge temperature, with the recovered heat subsequently returned to the cycle.

Concurrently, the hot compressed shell-side air is cooled to a low temperature which is set by the limiting "pinch point"; that point of closest approach in the temperature profiles of the two counter flowing streams. The low temperature air exits the high pressure heat exchanger and is piped to the recuperator at < 200ºF. The ship-based gas turbine can now take full advantage of the unlimited cooling capacity available. Alternatively, the air can be cooled further, say to the dew point of the air, by means of a cold seawater flow in an aft tube section of the heat exchanger. Every degree the compressed air temperature is lowered and the heat rejected results in a _ one degree lowering of the stack temperature in the recuperator and recovery of an equal amount of heat. Although this additional cooling appears to be a only a break-even proposition at best, it will be shown, when viewing the whole cycle, to be more significant than expected. It is believed the HPQX can effect cooling of the turbine exhaust more cost, weight, and volume effectively at high pressure than the HRSG at atmospheric pressure. The regenerator of high effectiveness can, in turn, be expected to lower the temperature of the exhaust gas to approximately its dew point.

An Option for Recouping Low Grade Heat the Cycle Now Rejects

The high pressure heat exchanger reduces the compressed air temperature to < 200ºF, or to near ambient temperature with a sea water aftercooler. This ultra cool compressed air would be the choice for the coolant for the turbine hot sections. This exchanger produces a performance dividend that can be divided between less compressor bleed air and / or raising the firing temperature. The source of cooling air may be deemed as "too cold" or at least below optimum for the very hot metal surfaces. There is a preheat solution for this "too cold" coolant. This is because low grade heat the cycle is normally forced to reject can now be recuperated.

The hot lubricating oil carries the heat lost in the bearings and the very large heat generated in the gearing down of the gas turbine shaft speed from ≈10000 RPM to the ≈100 RPM of the propeller. If the gas turbine drives a generator, the heat generated by the "copper losses" and the heat produced in the "iron losses" in the transformer are both eligible for recuperation to the cycle by the cool compressed air generated by the high pressure heat exchanger. The cool air, so preheated, is ready to act as the optimum turbine coolant.

3. STEAM INJECTION

Another of the long-identified methods to enhance gas turbine performance, even before employing a recuperator to recover heat in the exhaust, is to increase the volume flow of gas at the inlet to the power turbine. Particularly, if the gas, unlike air, requires no compressor work, steam is such a gas. Injecting steam raised from the gas turbine exhaust into the combustor has long been employed to augment gas turbine performance. To preserve the design surge margin, gas turbine manufacturers often limit the amount of steam that will be permitted to be injected to ≈ 5 percent of inlet air flow at base load. The surge limit can be increased if the first vane throat dimension is increased by "restaggering" the blades. Any quantity of steam can be injected if the turbine is redesigned.

Steam is often used for NO_x control. For instance, a steam flow of approximately 2.8 percent air flow is required to reduce NO_x to 42ppmv from a firing temperature of 2350ºF. At this temperature level, pound for pound steam injected in the advanced aeroderivative gas turbine combustor is approximately 3.5 times more effective than air in producing net power, i.e. the 5 percent steam flow will increase power output by ≈ 17.5 percent. The steam-to-fuel ratio is ≈ 2.5 / 1 at a steam injection rate of 5 percent of air flow. The work produced by the steam injected in the gas turbine can far exceed the work produced in the alternative disposition of the steam in a steam turbine. The difference in the two turbine inlet steam temperatures can be over 1500ºF. The gas turbine, steam injected, will produce 1 kilowatt of power for every 6 to 10 pounds per hour of steam injected.

The steam injected gas turbine (or Cheng cycle) is not a combined cycle. It is a quasi-simple cycle. Essentially, the steam injected gas turbine plant has two principal components 1) the gas turbine and 2) the heat recovery steam generator (HRSG). The reliability and availability factors of the HRSG, particularly of subcritical once-through designs with almost no moving mechanical parts, has proven to be close to 1.000. This implies that the overall plant availability is set almost entirely by that of the gas turbine availability (.96 to.98), and that other power plant configuration or arrangement with the same gas turbine could be expected to exceed this overall availability.

The HRSG capital cost is a precise commodity-class of purchase given the sizing parameters. {unfinished, more to be said}

What can be said of part load efficiency? A critical feature of economic operation of the ship propulsion gas turbines, as previously stated, is to maintain thermal efficiency at part load. Mr. Stanley C. Keller of GE Evandale Marketing Department, in a recent article in the spring of 1994 issue of, Cogeneration and Competitive Power Journal, suggests that steam injection provides an excellent method of fulfilling this primary requirement.

"Steam injection can also improve part-load efficiency. Single shaft gas turbines usually have poor efficiency at reduced load. *With steam injection, steam can displace fuel demand and raise the part load efficiency.*"

The Cheng cycle has been in commercial operation for about 15 years and has close to a million hours of operation. The General Electric steam injected aeroderivative plants have been in world-wide operation for about eight years. These gas turbines have been proposed for utility operations in unmanned plants. The only negative aspect of steam injection and of the subcritical once-through boilers is the demand for 100 percent makeup water of nearly the highest quality. This attribute prohibits consideration of such plants in water short areas or where the price or use restrictions of water makes an open cycle facility impractical. This paper will address the vexing water problem in a later discussion, with a proposed solution that seems particularly well suited for surface ship propulsion applications.

NO_x Abatement Alternative to SCR/NH_3 and to Dry Low NO_x Combustor

In addition to providing both augmentation in gas turbine power and an increase in efficiency, steam injection has long been employed to dilute peak flame temperatures and reduce the formation of oxides of nitrogen (the Zeldovich NO_x) that are otherwise formed in the gas turbine's combustion process. Unfortunately, steam dilution inhibits the combustion process and unburned products are formed such as carbon monoxide in rapidly increasing amounts as the NO_x is being reduced. Steam or water injection has long been the gas turbine manufacturer's recommendation for NO_x emission reduction. General Electric will guarantee 25 ppmv, with natural gas fueling, by this means. Further reduction from this guaranteed level has been the target of a major development effort by all gas turbine manufacturers. In the interim, for those areas in the world that have a critical air quality problem, Selective Catalytic Reduction (SCR) of NO_x with ammonia, with the catalyst bed suitably positioned in the gas turbine exhaust, has been deemed the best available NO_x control technology. Steam injection plus SCR will yield less than 9 ppmv of NO_x in the stack gas. Often the CO is also reduced by means of an oxidation catalyst positioned ahead of the SCR catalyst bed in the high temperature exhaust flow. Recently, the gas turbine manufacturers have developed, at considerable expense, and some are now operating, a dry low NO_x combustor. By premixing fuel and excess air (to a carefully controlled degree) the peak flame temperatures are reduced, enabling the lower NO_x concentrations (≤ 25 ppmv) to be achieved without steam injection or SCR.

If steam injection is employed for performance enhancement only, what are the coincident NO_x and CO levels that could result, without the new dry low NO_x combustor or use of SCR? On May 13, 1988, Dr. Donald W. Bahr, Manager of Combustion and Heat Transfer, General Electric M &I, Evandale, Ohio gave a presentation to the South Coast Air Quality Management District (SCAQMD) in El Monte, California. Dr Bahr presented this data for the two principal steam injected gas turbines GE is selling, the LM2500 and the LM5000, natural gas fueled:

FULL LOAD, WITH MAXIMUM STEAM INJECTION RATES

Gas Turbine	Steam Injected Lbs / Hr	Steam Fuel Ratio	No_x Ppm @ 15%O_2	Percent of Uncontrolled NOx	Accompanying Co Conc.Ppmv @ 15% O_2
LM2500	22,000	2.02	12	8	170
LM5000	37,000	2.41	13	6	167

The Figure 3. data shows that 1) NO_x can be reduced to 6 to 8 percent of the uncontrolled concentration and 2) the resulting CO concentration is unacceptable. The "maximum steam injection rates" are set by the combustibility limits of methane in this steam / air oxidizer. The exponential increase in CO is evidence of increasing combustion instability. If more steam were injected, combustion would be unsustainable and flame out would be imminent because the so called "lower lean limit" has been reached *for this particular fuel*. Gaseous fuels are categorized, on one basis, by their calorific value (Btu / ft^3). What is the effective calorific value of the steam diluted fuel burned in the above gas turbines? If the steam and methane (≈1000 Btu / ft^3) were supplied to the combustor premixed as a medium Btu fuel, would then have a diluted LHV heating value calculated as follows:

$$= 1000 \text{ Btu per ft}^3 / (2.41(\tfrac{16}{18})+1) = 318 \text{ Btu} / \text{Ft}^3$$

The foregoing combustion data on the GE engines speaks for itself. What is not said, however, is that chemical composition of the fuel is a factor, the gas turbine will support stable and efficient combustion with an even more dilute fuel <100 Btu / ft^3 fuel, provided sufficient hydrogen (10 to 15 percent) is present in the fuel. At this dilution of the fuel, at the "lower lean limit", an order of magnitude less NO_x and CO is expected to form. Where to economically get the hydrogen has long been the remaining question. An April 1993, study from GE Corporate Research and Development, "Evaluation of Reducing Gas Turbine Emissions through Hydrogen-Enhanced Steam-Injected Combustion" confirms this expected effect on emissions of Hydrogen in steam-injected combustion.

Does the marine gas turbine, for surface ship propulsion, have a compelling need for ultra low emissions? No it does not. It is believed, however, that if the fully enhanced marine gas turbine cycle is clean burning and comes with ultra low NO_x, all at no extra charge, it would not be resisted and certainly harbor masters around the world would be assuaged.

4. **REHEAT**

This reheat enhancement option is well known and has been recognized for its promise for increased performance. Reheat is even better known to the gas turbine manufacturers for its development risks and potential problems. The better known researchers and advocates of reheat gas turbines, Ivan G. Rice in 1982 and M.A. El-Masri in 1985 have long advocated development and adoption of this option.

The net shaft power derived from the gas turbine is a direct function of turbine efficiency and of the gas flow rate, temperature, pressure and composition of the gas entering the power turbine, with a deduct for compressor drive and its efficiency. In the case of the WR21 and the LM2500R, a separate free power turbine is employed. Many millions have been spent in the extraction of the last fraction of a point of efficiency in the compression / expansion through the compressors and turbines. Of the remaining variables offered, inlet temperature has long been a favorite target for conjecture. The problem: how to raise the power turbine inlet temperature and have something of a net performance gain left after the imposing deducts. One must assess the design penalties such as more compressor bleed air for cooling the massive power turbine, which is presently uncooled, development of flame holders, combustion cans, etc. and other performance reductions. Until 1993, the gas turbine manufacturers, to a firm, stated repeatedly for two decades that the speculative performance benefits of reheat did not outweigh the projected cost. If more power is needed, another gas turbine will supply it. In 1993 Asea Brown Boveri, undaunted by the challenge, and confident of the benefit, after three years of unpublicized development, announced that GT24 and GT26 gas turbines were for sale with reheat combustion.

The Reheat Combustor, a New Approach

Raising the temperature of the main gas flow entering the power turbine poses many development problems. In the judgment of all but one of the manufacturers the costs are likely to exceed the benefits. There appears to be a chemical way to finesse the mechanical barriers leading to a workable reheat combustor. This concept uses a hydrogen-rich fuel.

In August 1992, Southern California Edison contracted with Physical Sciences Inc. of Andover, Massachusetts, to conduct a feasibility study of a reheat combustion process for a gas turbine employing a low Btu hydrogen-rich fuel. The study found the fuel would autoignite spontaneously, no flame holder required, ignition time plus combustion time would be complete in less than 10 milliseconds, and no additional NO_x would be generated. The one condition: near ideal fuel / air mixing must be achieved. With that requirement in mind, the following physical combustion process is envisioned: The blade and vane cooling channels on the last turbine stage prior to the free power turbine would be used to introduce the hydrogen-rich fuel into the main air flow path. Normally, the trailing edges of the blades and vanes inject spent cooling air into the main air path through minute holes in what is carefully designed to be a completely uniform manner. The ignition delay time and the physical mixing time are not that dissimilar. The fuel flow would also perform the cooling task on the last turbine stage, normally done by the compressor bleed air.

How high can reheat combustion raise the temperature of the power turbine inlet gas flow (inviserated air plus combustion products)? Presently, the power turbine inlet temperature is ≈1500°F. At this temperature not only is cooling not required less expensive alloys can be employed. Thus, a materials upgrade alone i,e, super alloys, special castings and coatings, will allow several hundred degrees F higher power turbine inlet temperature. This could be called "quasi reheat." On the other hand, if unlimited cooling medium can be provided, the ultimate upper physical limit on the reheat firing temperature comes with the arrival of oxygen depletion. There is a way to produce the coolant flow necessary to effect the power turbine cooling that would allow for the raising of the gas path temperature without using any compressor bleed air, and thereby approach the goal of the combustibility limits, i.e. oxygen depletion.

5. **CLOSED LOOP COOLING OF THE POWER TURBINE**

Along with the quest for an economic reheat combustor, a decades-long search for an acceptable substitute for compressor bleed air for a hot section coolant has been underway. The search is over.

In May of 1995, General Electric Company announced a major breakthrough with the development of a power turbine whose blades and vanes employ the most advanced alloys, castings and coatings and are also cooled by steam. Additionally, the steam, after cooling the internal hot sections of the power turbine, is recovered and, with the additional superheat, is routed to an LP steam turbine, making what GE terms "a thermodynamically seamless combined cycle." GE says the rotor steam delivery system meets extremely tight limits for leakage. Steam is a superior coolant compared to air and the GE gas turbine firing temperature can now be raised from 2350ºF to 2600ºF. This allows specific work to be raised from an already remarkable .26 to an unprecedented .33 MW-sec per pound of inlet air. This together with net plant thermal efficiency over 60 percent.

As an example of the effect of ultra high specific power from the newest land based plant, at this specific power, the 9.3 MW of ship-board cruise power per engine could be supplied by 9.3/.33 or 28 pounds per second of air. At cruise power the WR21 ICR requires 86 pounds of inlet air per second.

The question is: "What specific work can a fully enhanced cycle be expected to deliver?" Such a cycle would make use of the GE development, the closed loop cooling of the power turbine as *one* of the performance enhancing techniques of a fully enhanced gas turbine.

Closed Circuit Cooling With An Alternate Coolant

The fully enhanced gas turbine cycle proposed in this paper would make use of a variation of the GE development. The power turbine would be cooled by a closed loop. The coolant need not be composed of steam only. The coolant would be the effluent from the heat recovery unit operating off of the gas turbine exhaust. For stationary power plant use, the effluent would be a reformed steam/methane mixture. For ship propulsion, the effluent would be a superheated mixture of distillate and steam. The HRSG feed would be an emulsion of distillate and water. The shipboard cycle would have a catalytic partial oxidation unit over which the superheated steam/hydrocarbon mixture would pass. With the addition of a certain amount of air, the chemical reaction partial oxidation would produce a hydrogen-rich fuel gas that would fuel both the reheat combustor and the primary combustor. This fuel would allow operation of the reheat combustor as previously described.

In summary, the power turbine can be cooled closed loop, and the reheat combustor made to work efficiently, as described, when the cycle is fueled with distillate.

6. CHEMICAL RECUPERATION

Recuperation of the gas turbine exhaust heat is normally accomplished by steam-raising. Sensible and latent heat is taken up by an in-tube counter current flow of water. The steam produced is heated further (superheated) to a temperature in close proximity to the gas turbine exhaust temperature. If the in-tube flow is a blend of water and hydrocarbon fuel, a process called steam distillation takes place. If the hydrocarbon is natural gas, as in the case of a power plant, the superheated mixture can, with the aid of a nickel catalyst, react chemically i.e. steam reform -- to produce a hydrogen-rich, highly combustible fuel gas. In the surface ship application of gas turbines, the standard fuel is a distillate petroleum fraction that cannot be easily steam reformed. The superheated steam/distillate vapor effluent can, however, react with a small amount of air in the presence of a suitable catalyst and, by partial oxidation, produce the same hydrogen-rich fuel gas.

Two Phase Feed to the HRSG

The gas turbine exhaust heat-recovery would employ a sub-critical once-through boiler. The steam distillation process taking place in the tubes not only produces an ideal feed for catalytic partial oxidation to produce hydrogen-rich fuel, but also has a thermodynamic advantage over use of water only. The water and hydrocarbon are immiscible, and each phase exerts it's own independent vapor pressure. As the temperature of the flow in the tube rises, steam and distillate vapor are formed at a temperature significantly less than with pure water or distillate. Unlike pure water, the temperature of the fluid mix continues to rise during the whole evaporation process. The "pinch point" restriction normally seen with steam is significantly lowered. Thus, the two phase feed recuperates a portion of the exhaust heat with the distillate flow and offers a thermodynamic benefit which is realized in the reduction in latent heat losses in the stack gas. (See figure 2)

Multi-Pressure Heat Recovery of Gas Turbine Exhaust Heat

Normally, a heat recovery steam generator may operate with one to three pressure levels and, in the case of a combined cycle, often the HP steam turbine exhaust steam is reheated before going to the IP steam turbine. The multi-pressure (and saturation temperature) levels allow the maximum heat to be removed from the gas turbine exhaust flow thereby minimizing the stack temperature and minimizing the three steam temperature approaches (to the exhaust gas) exiting the HRSG. The steam reheat reduces the overall water flow required by the HRSG to recover the said heat. Reheat effectively reduces the cycle losses associated with the latent heat of water when, in a combined cycle the steam turbine exhaust flow is condensed or, in the steam injected gas turbine cycle, the steam leaves up the stack along with the latent heat. The down side of the multi-pressure HRSG when employed with a steam injected gas turbine is that the steam flows associated with the two lower pressure levels, IP and LP, do not have sufficient pressure to enter the primary gas turbine combustor. Some 10 to 20 percent of the total steam raised in the ultra efficient multi-pressure HRSG must find a home in the cycle in the less than the optimum position, i.e. other than the high temperature gas turbine combustor.

The proposed scheme will allow all steam raised in the efficient multi-pressure boiler to go to the gas turbine combustor: 1) the high pressure steam will be raised at a pressure far in excess of the pressure required to enter the combustor 2) the intermediate pressure steam will be raised at the pressure required to enter the combustor 3) the low pressure steam will be raised at the pressure designed to maximize the heat recovery. Two options are available for combining the high and low pressure steam flows to the required pressure for combustor entry. An efficient single shaft steam turbine/steam compressor arrangement, or a less efficient thermocompressor with no moving parts, may be used to combine the three flows and make all the steam available to the cycle at the combustor pressure.

In the fully enhanced cycle being proposed, the liquid feed to the heat recovery unit is a two phase feed composed of hydrocarbon (distillate) and water as discussed earlier. The thermodynamic advantages of the two phase feed will be combined with the multi-pressure heat recovery and vapor compression discussed in the previous paragraph.

7. RECOVERY OF CYCLE WATER

As previously discussed, the steam injected gas turbine requires treated makeup water of nearly the highest quality. Depending on location, this water can be expensive, or even prohibitive if the availability and quality of the source water are not favorable. For example, ships on Siberian rivers, floating on distilled ice water, would pay the lowest cost for makeup water. Ironically, from the very beginning of sea travel, all oceangoing ships have been forced to pay any price in meeting the vital demands for water of *the right quality* for both men and machines.

In the fully enhanced gas turbine, the techniques and options of recovering both heat and water are evaluated against an economic yardstick. Since all of the ultra-quality water required by the cycle is contained in the stack gas flow, one need look no further for the first possible alternative source. If this source of makeup water is at all economically viable, the steam injected gas turbine power plant can then be located in places on land or sea that would otherwise be unsuitable for such a plant. There are many obvious tradeoffs in the several methods of recovering the water. All are beyond the scope of this paper. On the other hand, the physical requirements for condensation to occur in the stack gas are not at all ambiguous and are readily identified and evaluated as to achievability.

Briefly, the stack gas in the steam injected gas turbine is perhaps one third by volume water vapor, the partial pressure of water vapor is 1/3 of an atmosphere and the dew point is found to be ≈161°F. Cooling the stack gas further to ≈101°F will have condensed all of the necessary cycle makeup water. A titanium-tubed surface condenser with ocean water as coolant is one solution. A "dry" cooling tower is another. A third would be a direct cold or chilled water contact condenser. (See Figures 4 & 5) What is the quality of the condensed water? For a first approximation, at worst, the entire sulfur content of the fuel will be in the condensate as sulfurous or sulfuric acid. At ≈ 1/4 percent sulfur in the distillate the condensate would be ≈445 ppm sulfur. Passage through an anion bed and a polishing bed demineralizer should, in principle, restore the water to feedwater condition. Alternatively, the sulfuric acid could be neutralized and form a highly insoluble (≈ 1 PPM) filterable precipitate such as Barium Sulfate, negating the demineralizer. Can any water recovery process be certified for sea duty? The first requirement, that it work effectively in land based plants, has been met.

The first land based plant employing a steam injected gas turbine with recovery of the injected water began operation in January, 1993, near Turin, Italy. The design of the plant and operating features are covered in detail in the 1994 ASME paper, 94-GT-17, by Ennio Macchi and Aurelio Poggio given in the Hague in June, 1994. In this plant, the next additional and more complex step is taken in that the latent heat of condensation is recovered and used in a cogeneration mode. This is also possible for surface ships. Other shipboard energy needs, space heating and hot water could be met in a similar manner.

FULLY ENHANCED GAS TURBINE SPECIFIED FOR A SURFACE SHIP

From a review of the available options for enhancing the performance of a gas turbine, certifiable for sea duty, the following cycle is proposed as the fully enhanced gas turbine.

Intercooled Compression

The decision on the use of an intercooler requires a careful analysis. Is the initial compression to employ an intercooled as in the WR21 unit, or operate without an intercooler as the 2500R? The heat removed in the intercooler is normally too cool to be recovered for a useful purpose and will be rejected in a sea water exchanger, and will be an energy debit to the cycle. The intercooler may still be appropriate depending on the gas turbine selected.

The High Pressure Heat Exchanger

The cycle will use a two-section high pressure heat exchanger (HPQX). The high temperature, high pressure compressor (HPC) discharge air will be diverted to the HPQX where the air will be cooled to within the limits imposed by the HPQX "pinch point". The high pressure air will be cooled further by a final seawater cooled aftercooler section within the HPQX, the heat removed being rejected. Ideally, the recuperator will then allow the gas turbine exhaust flow to be cooled down to the dew point, returning the heat removed to the cycle and in anticipation of condensing the water vapor in a following step. The diversion of the HPC air is identical in concept with the WR21 and the LM2500R gas turbine cycles. In both of those cycles, however, the HPC discharge air is routed directly to the recuperator. The HPQX is the new equipment in the cycle, positioned before the recuperator.

If an intercooler is used, the HPC discharge air temperature will be several hundred degrees lower than if no intercooler is employed. Due to the "pinch point" limitation, the final HPC air temperature is actually lower when the initial HPC temperature is greater. In addition to avoiding rejecting any cycle heat, the heat transfer duty (Btu/hr) will be greater without the intercooler. The opportunity to return more heat to the cycle in the form of steam is therefore greater. Furthermore, the cooler the HPC air is before entering the sea-water cooled aftercooler section, the less heat is lost to the cycle. Whether an intercooler is used or not, the colder sea water temperature will then readily allow the HPC discharge air temperature to be cooled further in the after cooler section, down to around ≈135°F. This, in turn, will then allow the recuperator to cool the gas turbine exhaust to a final stack gas temperature to the ≈165°F dew point. This allows the recuperator an assumed reasonable terminal temperature difference of ≈30°F. A portion of the 135°F HPC discharge air will be employed to cool the turbine hot sections. If the cool-air temperature is deemed below the optimum temperature, the plant ancillary low grade heat loads (hot lube and transformer oils) now being rejected would be used to preheat the cold air allocated for turbine cooling.

The Primary Surface Recuperator

In the case of natural gas fueling, more particularly methane, the total moles in the exhaust flow are equal to the sum of the moles of inlet air, recuperation water, and methane. Thus, if the air flow only is to recuperate heat from the total gas flow there is mismatched molar (or volume) flow. The cooling air deduction adds to the regenerator molar flow imbalance. The thermodynamics are improved if the gas flows are balanced, particularly if the difference is allowed for in the average specific heats. The heat-carrying capacities of the two streams are equal and the resulting hot-end and cold-end temperature approaches are approximately equal. To achieve the desired molar balance, a portion of the turbine exhaust gas flow does not flow through the recuperator. Instead, that portion (the remaining unmatched exhaust gas) flows through a separate parallel heat exchanger. This once-through tubular exchanger employs the same fuel/water feed as the HPQX to recuperate the remaining turbine exhaust heat in the unmatched exhaust flow.

The Parallel Exhaust Heat Recovery Unit

The gas turbine exhaust flow is precisely divided between the recuperator and a second, conventional once-through tubular heat recovery unit operating in parallel with the recuperator. The heat in this portion of the exhaust flow is recuperated by the in-tube flow of a mixture of distillate and water (the same heat recovery fluid as used in the HPQX). In is expected that the reheat combustion will raise the power turbine inlet temperature 500° to 900°F. The turbine exhaust flow is then anticipated to be 200° to 400° hotter than the compressor discharge temperature, the effluent from the HPQX is eligible to be superheated further by effecting a close approach to the exhaust temperature. The heat remaining in this portion of the exhaust flow after superheating the HPQX effluent is the heat recovered by the fuel / water mix. The two flows of steam / distillate vapor are joined to form the total fuel flow to the partial oxidation unit prior to injection into the gas turbine combustors. The cooled exhaust gas exiting the exchanger joins the cooled exhaust gas exiting the recuperator which represents the total stack gas flow. This exhaust gas is then ready to condense, filter and recycled the water content.

The Free Power Turbine, Closed loop cooled

As previously described, the free power turbine is expected to be cooled by using the flow of fuel gas composed of steam and superheated distillate. The fuel gas will be recovered from the power turbine after effecting the necessary cooling. The fuel flow is more than adequate to provide the required cooling with a relatively small rise in temperature. This is predicated on a firing temperature approximately the same as the primary combustor. The large coolant flow together with blades and vanes made of superalloys, special castings and gas-side coatings will support a considerably higher firing temperature. This coolant is superior to air at this elevated temperature in that antioxidation coatings on the internal metal surfaces will not be required. Stoichiometric combustion in the reheat combustor is a distinct possibility, particularly with sufficient steam injection. Power turbine exhaust temperatures will not limit stoichiometric firing temperatures in the reheat combustor. Existing alloys and materials will allow close approach temperatures.

The Partial Oxidation Unit

The high temperature flow of steam and superheated distillate exiting the power turbine will be premixed with a small stream of high temperature air and passed through a bed of partial oxidation catalyst. The effluent from this bed will be a high temperature, Hydrogen-rich fuel gas capable of autoignition and yielding ultra low NO_x. This fuel gas will fire both the primary combustor and the reheat combustor.

The Reheat Combustor

This reheat combustor will rely on the existing technology associated with blade and vane cooling and the unique combustibility of Hydrogen. There will be no hardware such as that associated with the primary combustor. The high temperature Hydrogen-rich auto-ignitable, low NO_x fuel gas will be introduced into the main air path from the trailing edge of the blades and vanes of the last turbine stage prior to entry into the free power turbine. The fuel flow will also provide the cooling for the last stage turbine blade and vanes.

Cycle Water Recovery

Cycle water will be recovered by a direct-contact cold water fog condenser with a secondary warm condensate-to-sea water Titanium tubed heat exchanger (see Figures 4.& 5.) The dilute sulfuric acid in the condensate will be neutralized with Barium Carbonate and the precipitate filtered out. The Sulfate can be converted continuously (57 lb / hr) to the carbonate.

PROJECTED PERFORMANCE OF FULLY ENHANCED GAS TURBINE

The ultimate performance achieved by the fully enhanced cycle depends in part on the basic level of the gas turbine technology employed (firing temperatures and compression ratios). This requires turbine blades and vanes configured with state-of-the-art aerodynamics, constructed of the most advanced alloys cast as a single crystal, coated with the most effective thermal barrier coatings, employing advanced cooling strategies. The cycle steam-raising capacity and the steam-assimilating capacity of the gas turbine must match and be optimized, i.e. the "passing capacity" design of the turbines must recognize the combined air / steam volume flow expected in the optimized steam / gas turbine engine. The gain in the enhanced cycle performance, starting with the unique advanced gas turbine as described, can be significant. For instance, the very advanced (2600F and 23.2 / 1 compression ratio) and highly performing GE H cycle, has a net cycle specific work of .3252 Mwe-sec per pound of inlet air and yet requires 241 percent more air to be processed than the chemical stoichiometry requires. That is, if the oxygen were burned out by steam dilution and / or a second burn in series or both, the thermal power released would be 2.41 times as great. The specific work is a product of thermal efficiency and oxygen burnout efficiency times the stoichiometric heat release of 1.308 Mwt-sec per pound of air.

Can the oxygen be burned out? Can the efficiency be maintained with increasing steam injection? Initially, the injection of steam into the combustor simultaneously raises the power output and efficiency (steam requires no deduct for compressor work, and with maximum preheat before combustor entry) and burns up additional portion of the remaining oxygen. Eventually, as more of the steam is raised inefficiently (no superheat) with greater thermodynamic loss the cycle thermal efficiency peaks and declines with further steam injection. Power continues to increase. The several rhetorical question posed: can the GE H cycle offer greater performance as a steam injected gas turbine than in conjunction with a steam turbine? If reheat were an option (which it is not in this engine) could the oxygen be burned out with steam injection and a modest second firing temperature? Would the efficiency exceed the 60 percent cycle efficiency now achieved? And a pertinent question for GE: what would be the effect on overall plant economics of eliminating the steam cycle by the alternative of steam injection? If the oxygen can be consumed by steam injection and reheat in a marine engine, what size engine (air flow) would supply the cruise power of 9.3 Mws? At an assumed efficiency of 50 percent the air flow required = 9.3 / .5 / 1.308 = 14.22 lbs / sec, a far smaller engine. The following study reports on use of an earlier less advanced engine employed in a less enhanced steam injected and reheat cycle. The peak cycle efficiency was determined to be 43.68 percent, the stoichiometric efficiency at maximum power was 35.17 percent.

Herman B. Urbach of the Naval Surface Warfare Center, Annapolis, Maryland in a 1993 ASME paper, Titled, " A Study of the Feasibility of Steam-Augmented Gas turbines for Surface Ships" employed a reheat combustor and massive steam injection to achieve stoichiometric combustion, the physical limit on thermal power. The thermal and shaft power for methane and ambient air @ 20.734 percent Oxygen:

@59ºF

Reaction $CH_4 + 2O_2 \rightarrow 2H_2O + CO_2$ -345,210 Btu / lb mole

Air required = 2 / .20734 = 9.646 moles = 278.335 lbs.

Heat / lb air= 345,210 / 278.335 = 1240.27 Btu / lb
=1754.77 Hp-Sec / lb

Air / distillate ratio at stoichiometric comb.= 15.186 lb / lb

$$\text{Distillate fuel} = \frac{18300 \text{ Btu / lb}}{15.186 \text{ lb / lb}} = 1205.06 \text{ Btu / lb of air}$$
= 1704.96 Hp-Sec / lb of air

In the aforementioned study, stoichiometric combustion was achieved with a steam injection flow equal to 49.47 percent of inlet air flow. The firing temperature of the gas turbine combustor and the reheat combustor were 2200ºF and 1900ºF respectively with a 16 atmosphere gas turbine combustor pressure. The cycle thermal efficiency was found to be 35.17 percent. The shaft work per pound of air ***for stoichiometric steam injection*** is given by:

= .3517(1704.96) = 599.63 Hp-Sec / lb of air

The gas turbine air flow was 84.1 lb / sec, the shaft power is :
= 84.1(599.63) = 50,429 Horsepower

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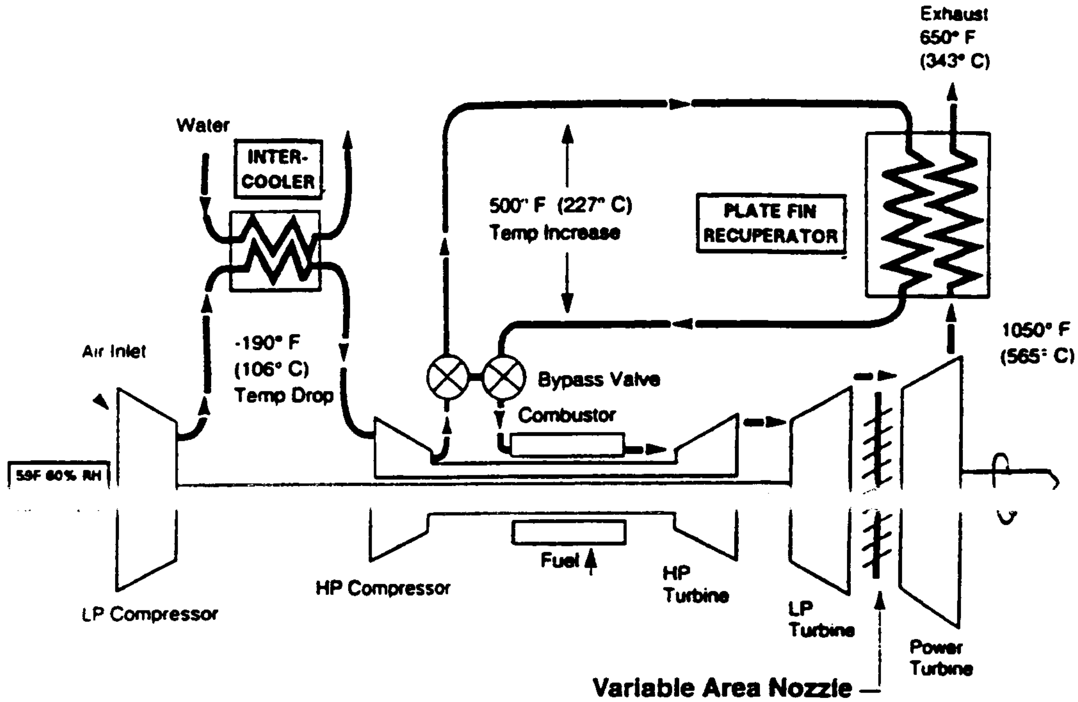
APPENDICES

Conversion of the English Units for temperature, pounds and British Thermal Units (Btu) to the SU I units is accomplished as follows:

C° = (F° - 32) * 5 / 9
Kilograms = 2.2046 (pounds)
Kcalorie = Btu / .252

WR-21 Intercooled/Recuperated Cycle

Design features a two-shaft core engine with intercooling between the LP and HP compressor, recuperation of exhaust heat between HP compressor outlet and combustor inlet; and a free power turbine with variable area nozzle.



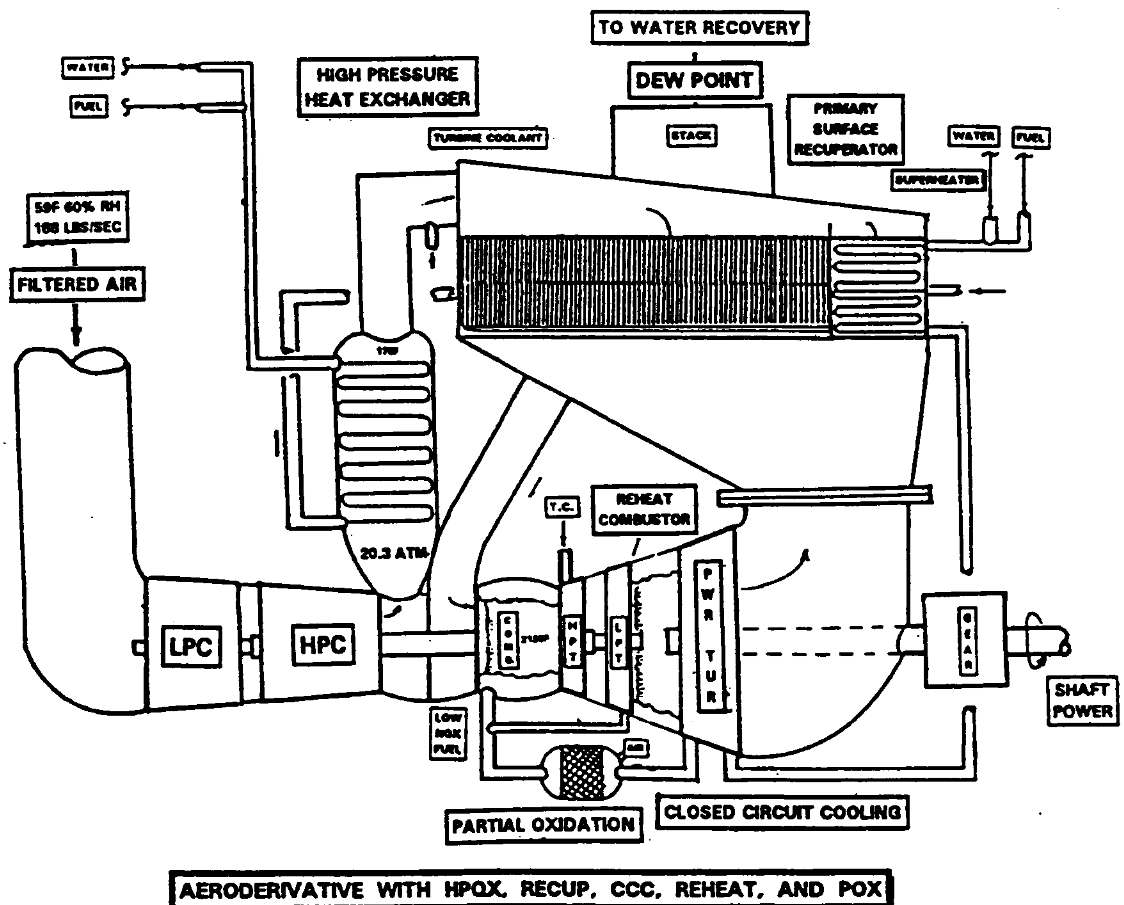


Figure 1. A partially recuperated cycle and a fully enhanced cycle.

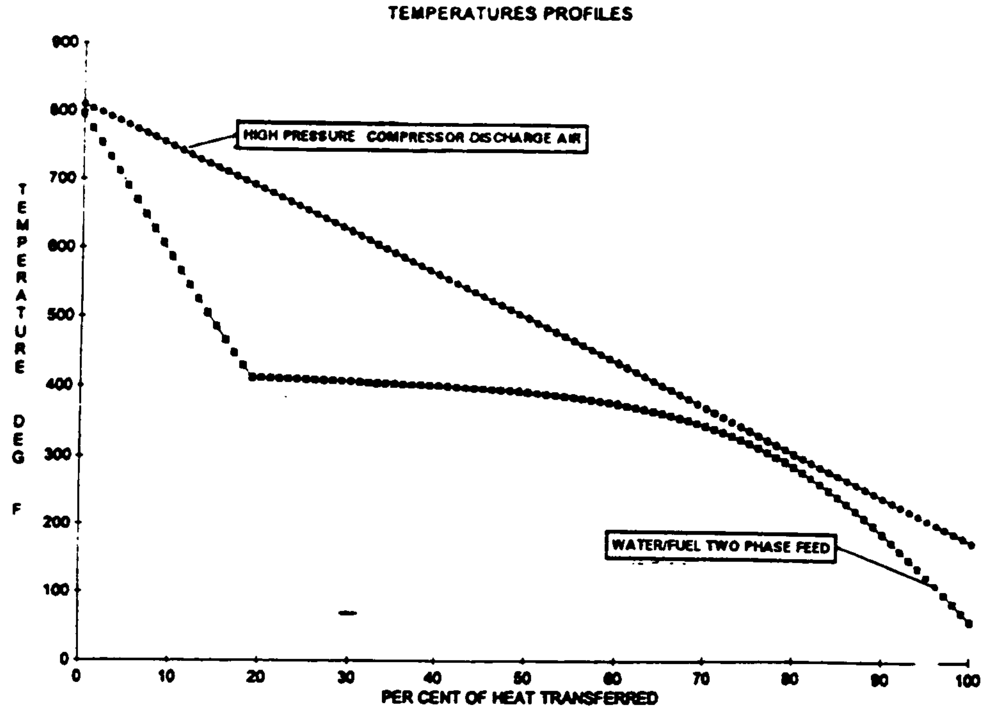


Figure 2. Temperature of the two counter current flows in the HP heat exchanger.

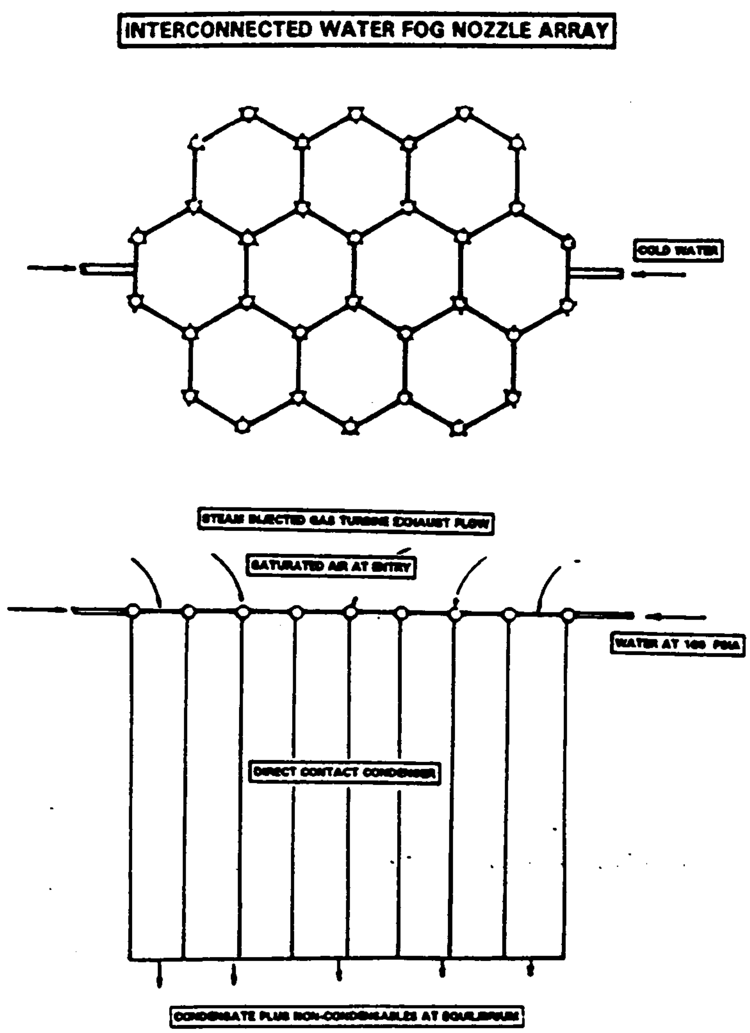


Figure 4. Nozzle array for direct contact condenser.

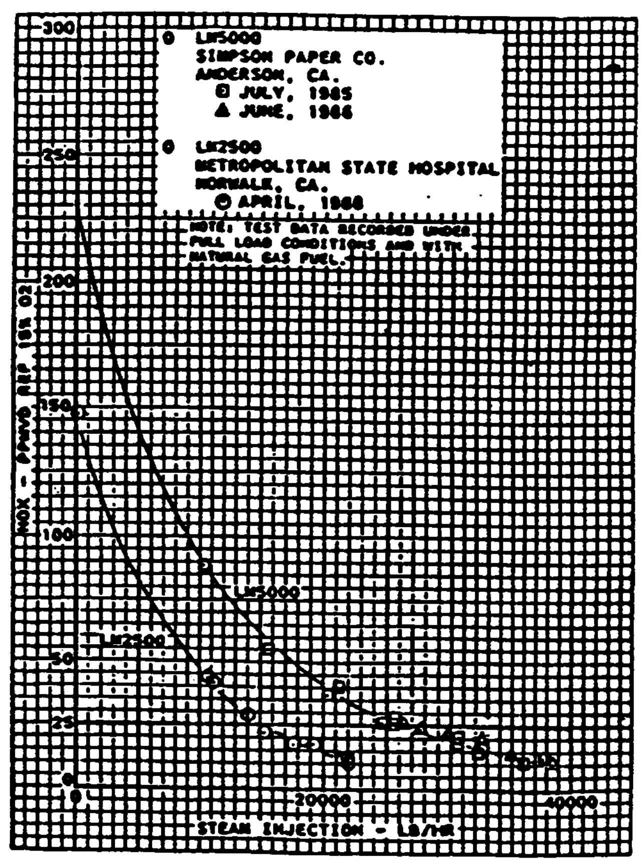


Figure 3. NOx reduction in GE gas turbines from steam injection.

WATER RECOVERY FOR STEAM INJECTED GAS TURBINE

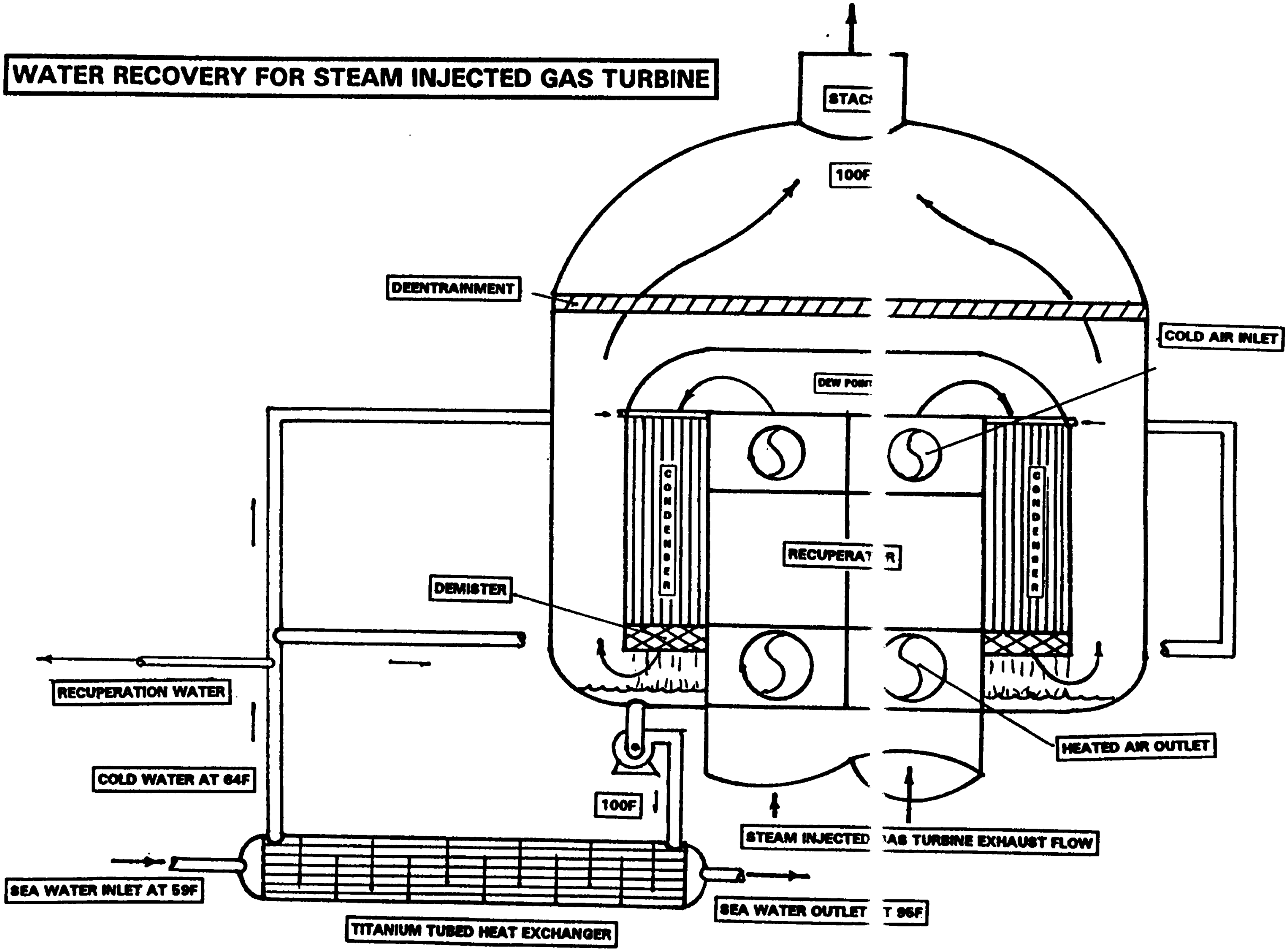


Figure 5. Water recovery from gas turbine exhaust with direct contact v ter fog condenser.